Fermi National Accelerator Laboratory

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A 3 TeV on 3 TeV Proton-Proton Dedicated Collider for Fermilab

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The Fermilab Dedicated Collider proposed in May 1983 is a 2 TeV on 2 TeV $p\bar{p}$ collider. (We ignore for the moment the ep option.) The expected luminosity is ~ 10^{31} $cm^{-2}sec^{-1}$ and the estimated cost is ~ $362M (FY-83 dollars). Since 1983 both the superconducting magnet and the particle detector technologies have advanced and the countenance of physics, hence the desired characteristics of new facilities have also altered somewhat. We want to show here that with the new magnet technology used for the SSC one can construct a 3 TeV on 3 TeV pp collider on the Fermilab site. This pp Dedicated Collider (PPDC) will have a luminosity of about $10^{33}cm^{-2}sec^{-1}$ and a cost only ~ 50% more than that of the $p\bar{p}$ Dedicated Collider.

1. Rationale and Development of Concept

Compared to $p\bar{p}$ a pp collider has two major advantages:

a. Much higher luminosity, and

b. The injector is freed after filling.

For $p\bar{p}$ the injector is generally occupied full-time for $\bar{p}$ production, whereas with PPDC more than 90% of the time the Tevatron is free to carry out its own fixed target or $p\bar{p}$ collider programs.

Because of the need of bringing the two proton beams to collide nearly head-on the interaction region (IR) for a pp collider is necessarily longer than that of a $p\bar{p}$ collider. The design of the IR for the SSC which was patterned after for the Tevatron pp Upgrade is near optimal, and will again be adopted here. In this design the beams are brought together vertically and are focused to low-β waists at the collision point by common quadrupole triplets. Interpolating between the 125m length at 1 TeV and the 1150 m length at 20 TeV we obtain a total length for the IR of PPDC of ~ 300 m at 3 TeV. (The details will be given later. One notes here that the length is roughly proportional to the 3/4 th power of the energy.)

For 3 TeV, $B\rho$ = 10010 Tm. If one uses the 6.6T SSC dipole one gets $2\pi\rho$ = 9530m. A dipole packing fraction of ~ 85% in the regular arcs is easy to obtain. Thus the total circumference of the ring is

$$2\pi R \cong \frac{2\pi\rho}{0.85} + 8 \times 300 \text{ m} \cong 13612 \text{ m}$$

or

$$R \cong 2166 \text{ m}$$

where we have assumed as in the case of the $p\bar{p}$ Dedicated Collider that there are 8 straight sections in the PPDC. A tunnel of this radius fits gracefully in the Fermilab site as was shown with the design of the $p\bar{p}$ Dedicated Collider.

2. Low-β Interaction Region Design

This is similar to that of the Tevatron pp Upgrade and patterned after that of the SSC. Fig. 1 is very similar to Fig. 2 of TM-1467. Starting from the interaction point (IP) we have in sequence:

A drift space for detector of ± 10m ($\overline{AB} \cong$ 10m),

A common quad triplet to produce low-β ($\beta*$ = 1m, $\overline{BC} \cong$ 18m),

A common vertical dipole to separate the beams

$$\begin{pmatrix} B\ell = 6.6\text{T} \times 7.5\text{m giving} \pm 5\text{mrad} \\ \text{Bore diameter} \gtrsim 5 \text{ cm}, \ \overline{CD} \cong 8\text{m} \end{pmatrix},$$

A number ($\gtrsim$ 4) of staggered quads to match to the optics in the arc ($\overline{DE} \cong$ 110m),

Two ''mirror'' vertical dipoles to bend the beams back to horizontal ($B\ell$ = 6.6T × 7.5m, $\overline{EF} \cong$ 8m. These dipoles may be located forward in between the matching quads to reduce the ring separation).

This gives a total length for the IR of 308m which is intentionally adjusted to equal the length of 4 normal arc cells. The reason for this adjustment will be made clear later. The details of the IR have yet to be worked out, but there is no doubt that with these dimensions one can obtain the desired zero dispersion and β^* = 1m at the IP.

3. Normal Arc Design

We use the time-tested 90° FODO cells. Fig. 2 shows half of a normal cell. Instead of the four 8.5m dipoles it is clearly possible to use two 17m SSC dipoles in a half cell, except for 17m dipoles the orbit sagitta is ~ 2.4cm and the dipoles must be curved.

4. Ring Parameters

<u>Octant arc</u>

Total length = 1424.5m

Cell length = 77m

Number of cells = 18.5

Dipole length = 8.5m

Dipole field at 3 TeV = 6.6T

Number of dipoles = 17.5 × 8 = 140

(with a dispersion suppressor at each end)

Quadrupole length = 1.7m

Quadrupole gradient at 3 TeV = 217 T/m

Number of quadrupoles = 18.5 × 2 = 37

Phase advance per cell = 90°

Tune advance = 4.625

$\beta_{max} \cong 131m$ $\beta_{min} \cong 23m$

$D_{max} \cong 2.34m$ $D_{min} \cong 1.12m$

Low-β interaction region (IR)

Total length = 308m

Number of vertical dipoles = 6

Number of quadrupoles $\cong$ 24

Tune advance $\cong$ 2.25

Utility region (UR)

Total length = 308m

Number of quadrupoles = 8

Tune advance = 1 (4 straight normal arc cells)

One whole ring (assuming 4 IR's and 4 UR's)

Circumference = 13860m = $2\pi R$

Equivalent radius = R = 2206m

Number of arc dipoles = 1120

Number of arc quadrupoles = 328

Number of IR vertical dipoles = 24

Number of IR quadrupoles $\cong$ 96

Tune = $8 \times 4.625 + 4 \times 2.25 + 4 \times 1 = 50$

5. Injection Options

Fig. 3 shows one possible layout of the 2.2 km diameter PPDC on the Fermilab site. This diagram also indicates that there are a number of options for injector and injection geometry:

a. Injecting at 1 TeV from the Tevatron

Then the PPDC magnets only have to ramp over a range of 3:1. Injection would be easy if the Tevatron could be operated in a bipolar mode. The oppositely circulating beams would be single-turn extracted at E0 and injected into PPDC UR's I and VII. The injection transport lines are rather long, but the total bend-angle is only ~ 90°. If the Tevatron could only be operated unipolar the total length and bend-angle of the two opposite injection lines would have to be much greater and the cost might be prohibitive.

b. Injecting at 150 GeV from the Main Ring (MR)

If the PPDC magnets can be ramped over a 20:1 range similar to that of the SSC magnets, we can inject directly from the MR at 150 GeV. The Tevatron ring is then left untouched and may be doing $p\bar{p}$ collider physics while the PPDC is being injected. In this case, even if the MR is operated only unipolar we can extract the beam at E0 for injection into the clockwise PPDC ring and at F0 (or F17) for injection into the counterclockwise ring. The injection point for both beams can be at UR I as shown in Fig. 3. The ~ 195° bend of the reverse injection beam can be fashioned out of the spare dipoles which could be removed from the MR since it is now operated only at 150 GeV. The total length of the injection tunnels is no greater than that for 1 TeV injection from a bipolar Tevatron.

There is no need to work out the details at this time. It suffices to show that there are a number of options available. The preferred option is clearly injection at 150 GeV (or a somewhat higher energy) from a unipolar main ring.

6. The Refrigeration, Vacuum, RF, Controls, Corrrection Magnet, Beam Abort and Extraction Systems, etc.

At this stage there is no need to do a detailed design for these systems most of which could be modified or scaled from those of the 1983 $p\bar{p}$ Fermilab Dedicated Collider. Some of these systems are actually simpler and cheaper than those of the $p\bar{p}$ collider. For example, the heat leak of the SSC type magnets is such that even for the two 3 TeV rings of PPDC the refrigeration requirement is less than that of the single 1 TeV ring of the $p\bar{p}$ Dedicated Collider.

We do not anticipate any difficulty in the design of any of these systems.

7. Beam Performance

a. Single beam instabilities

With moderate care in the construction of the beam pipes these instabilities have never been and are not expected to be of any problem.

b. Luminosity and tune shift

With

Bunch frequency = f = 53 MHz,

Protons/bunch = $N = 5 \times 10^{10}$,

95% normalized emittance = $\epsilon_n = 10\pi$ mm-mrad,

Low-β at IP = $\beta^* = 1$m,

At 3 TeV, $\gamma = 3198$,

Classical proton radius = $r_o = 1.535 \times 10^{-18}$m,

we get the luminosity

$$L = f \frac{\gamma N^2}{\epsilon_n \beta^*} = 1.35 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$$

and the linear beam-beam tune shift per crossing

$$\xi = \frac{r_o N}{\epsilon_n} = 0.0024 \qquad \text{(O.K)}$$

Thus, it is realistic to expect a luminosity of 10^{33} cm^{-2} sec^{-1}.

c. ''Reach'' comparison

With the Llewellyn-Smith scaling of ''Reach,'' namely

$$\text{``Reach''} \propto (\sqrt{s})^{2/3} \; (L)^{1/6}$$

for the three colliders:

1 TeV on 1 TeV,	$10^{30}cm^{-2}sec^{-1}$	Tevatron Collider
3 TeV on 3 TeV,	$10^{33}cm^{-2}sec^{-1}$	PPDC
20 TeV on 20 TeV,	$10^{33}cm^{-2}sec^{-1}$	SSC

we get ''Reaches'' in the ratio of

1 : 6.6 : 23.3.

Thus, the ''Reach'' of PPDC is 6.6 times that of the present Tevatron Collider and only a factor of $(3.5)^{-1}$ lower than that of the SSC. Of course, ''Reach'' is not the only measure of the usefulness of a collider, but it does give a rough overall comparison.

d. ep Option

Although so far it has not been mentioned, the ep option exists for the PPDC in almost an identical manner as that for the $p\bar{p}$ Dedicated Collider.

8. Cost

A rough cost estimate can be obtained by scaling from that of the $p\bar{p}$ Dedicated Collider. The scaling rules followed are:

a. The same cost per meter is used for the 6.6T SSC type magnets. Comparing the SSC and the DC estimates, namely

   16.6M SSC dipole = $120k (FY-87 dollar)

   7.8M DC dipole = $ 54k (FY-83 dollar)

   we see that the per-meter cost of the SSC magnet is no higher (perhaps even a little lower) than that of the DC magnet.

b. As mentioned before, the refrigeration requirement for both PPDC rings is no higher than that for the single DC ring. Therefore for Technical Components we double the costs of

Magnets and Accelerator Systems but keep the same cost for Refrigeration.

c. We double the cost and the contingency for Installation and Testing, and double the EDIA and the Contingency for Technical Components.

d. The cost, the EDIA and the Contingency of Conventional Facilities are all kept unchanged.

Following these rules we obtain from Table VII-1 on page VII-2 of the ''Proposal for a Dedicated Collider at the Fermi National Accelerator Laboratory'' (May, 1983) the following cost estimate for PPDC.

Technical Components		\$307 M
Magnets	215	
Refrigeration	27	
Accelerator Systems	65	
Conventional Facilities		\$105 M
Storage Ring Facilities	70	
Expt'l Halls & Assembly Areas	35	
Testing and Installation		\$29 M
EDIA		\$49 M
Technical Components	33	
Conventional Facilities	16	
Contingency		\$66 M
Technical Components	41	
Conventional Facilities	18	
Installation & Testing	7	
	Total	\$ 556 M

(FY-83 dollars)

The escalation rate between FY-83 and FY-88 is between 3% and 4% per year. We could, of course, get the actual data, but for the present purpose it is hardly worth the trouble. It is probably not too far off to take a total escalation over the 5-year period of ~ 18% and arrive at an estimated cost of about

$650 M (FY-88 dollars)

for the 3 TeV on 3 TeV, 10^{33} cm^{-2} sec^{-1} pp Dedicated Collider for Fermilab.

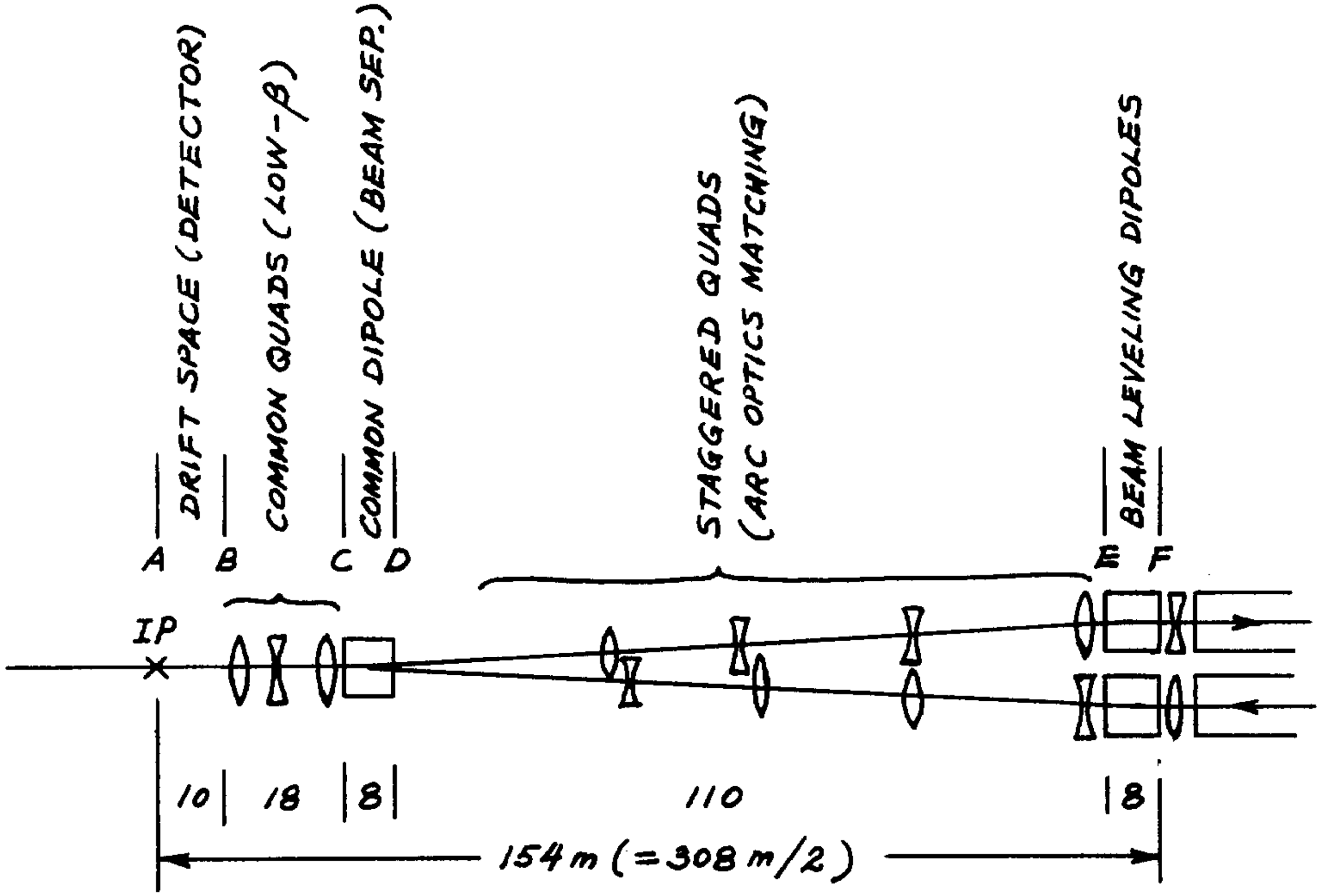

Figure 1. Half of a low-β interaction region. The beams are separated vertically.

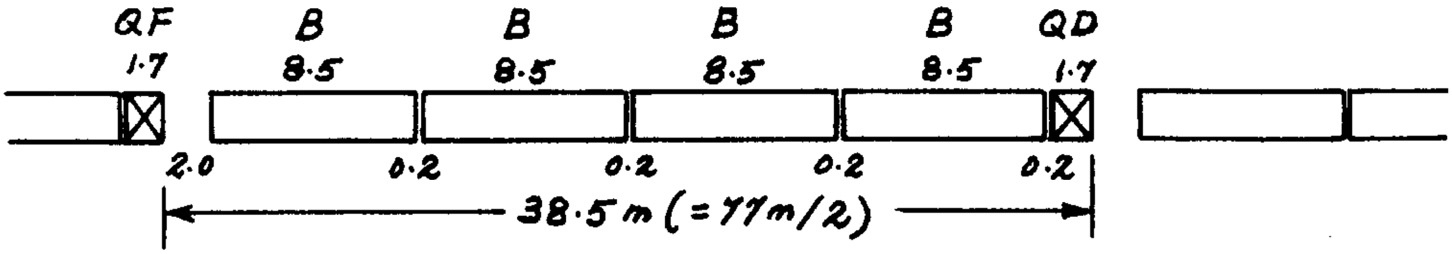

Figure 2. Half of a normal arc cell.

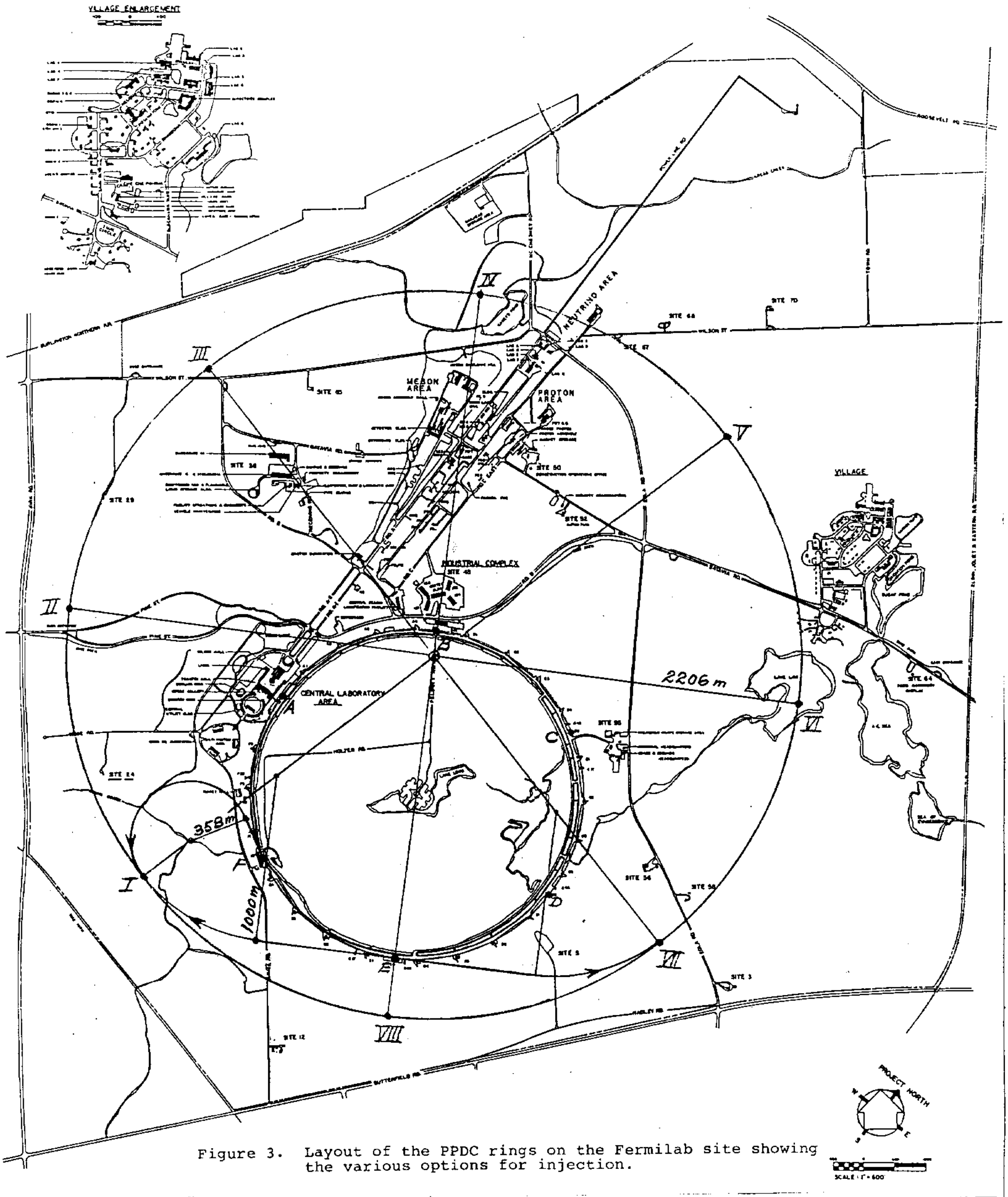

Figure 3. Layout of the PPDC rings on the Fermilab site showing the various options for injection.

FERMILAB SITE LOCATION PLAN